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A reference model for evaluating control strategies in activated sludge wastewater treatment plants

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Résumé de l'article

Dans la majorité des pays, il existe des lois strictes pour réglementer la qualité de l'eau provenant des systèmes de traitement d'eaux usées. Ces spécifications légales sont essentiellement influencées par des questions telles que la santé publique, l'environnement et les facteurs économiques.

Les objectifs fondamentaux des procédés de traitement des eaux usées sont d'atteindre, avec l'utilisation d'énergie et à des coûts opérationnels minimaux, une concentration de matière biodégradable et de nutriments suffisamment basse dans les effluents et une production minimale de boues.

Les systèmes de traitement des eaux usées sont de grandes dimensions et complexes. Ils sont aussi sujets à des variations importantes dans le flux d'entrée et dans la composition de l'eau à l'entrée, qui ne sont pas bien connues. Le procédé est multivariable, avec beaucoup de couplages croisés et nonlinéarités importantes. La dynamique dépend de la variabilité des flux d'entrée et de la complexité des phénomènes physico-chimiques et biochimiques. Le comportement dynamique démontre une énorme variation de temps de réponse (de quelques minutes jusqu'à plusieurs jours). Ces problèmes, combinés aux objectifs les plus importants du traitement des eaux usées, donnent lieu à une demande de techniques de commande avancées, qui peuvent conduire à une réduction du volume à traiter, une diminution importante dans l'utilisation des produits chimiques, et une possibilité d'économie d'énergie et une diminution des coûts d'opération.

Dans ce travail, un " *benchmark* " (modèle de référence) d'un système complet de traitement des eaux usées a été développé, pour évaluer, à partir de simulations, la performance des différentes stratégies de commande proposées, y compris les techniques de respirométrie ("respirometry"). Ce travail s'aparente au Programme Européen d'Action COST (COST 624), et au projet "Respirometry in Control of the Activated Sludge Process (IWA Respirometry Task Group").

Le "Benchmark" représente un procédé de prédénitrification de la boue activée pour éliminer la matière organique et l'azote des effluents domestiques. Le simulateur est basé sur des modèles largement acceptés par la communauté internationale et il a été implanté dans un environnement Matlab/Simulink. La topologie du système et le développement complet du simulateur sont présentés dans ce travail. L'effet des conditions initiales et des caractéristiques du flux d'entrée (valeurs moyennes) sont analysés, aussi bien qu'un test en boucle ouverte. Les stratégies suivantes ont été sélectionnées en guise d'illustration de l'application de la commande automatique dans le "benchmark" (seulement avec commande proportionnel-intégral monovariable): commande basée sur la concentration d'oxygène dissous ("DO concentration-based control"), commande par respirométrie (commande par biomasse active et commande par taux de respiration bactérienne), et commande par concentration de nitrate (commande par dosage externe de carbone et recyclage du flux interne). Le "benchmark" est continuellement mis a jour et sa prochaine version va incorporer des fonctions d'optimisation en temps réel (on line) pour le procédé.

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A reference model for evaluating control strategies in activated sludge wastewater treatment plants

Modèle de référence pour évaluer différentes stratégies de contrôle dans des usines de traitement des eaux usées

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RÉSUMÉ

Dans la majorité des pays, il existe des lois strictes pour réglementer la qualité de l'eau provenant des systèmes de traitement d'eaux usées. Ces spécifications légales sont essentiellement influencées par des questions telles que la santé publique, l'environnement et les facteurs économiques.

Les objectifs fondamentaux des procédés de traitement des eaux usées sont d'atteindre, avec l'utilisation d'énergie et à des coûts opérationnels minimaux, une concentration de matière biodégradable et de nutriments, suffisamment basse dans les effluents et une production minimale de boues.

Les systèmes de traitement des eaux usées sont de grandes dimensions et complexes. Ils sont aussi sujets à des variations importantes, dans le flux d'entrée et dans la composition de l'eau à l'entrée, qui ne sont pas bien connues. Le procédé est multivariable, avec beaucoup de couplages croisés et nonlinéarités importantes. La dynamique dépend de la variabilité des flux d'entrée et de la complexité des phénomènes physicochimiques et biochimiques. Le comportement dynamique démontre une énorme variation de temps de réponse (de quelques minutes jusqu'à plusieurs jours). Ces problèmes, combinés aux objectifs les plus importants du traitement des eaux usées, donnent lieu à une demande de techniques de commande avancées, qui peuvent conduire à une réduction du volume à traiter, une diminution importante dans l'utilisation des produits chimiques, et une possibilité d'économie d'énergie et une diminution des coûts d'opération.

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Dans ce travail, un « benchmark » (modèle de référence) d'un système complet de traitement des eaux usées a été développé, pour évaluer, à partir de simulations, la performance des différentes stratégies de commande proposées, y compris les techniques de respirométrie (« respirometry »). Ce travail s'apparente au Programme européen d'Action COST (COST 624), et au projet « Respirometry in Control of the Activated Sludge Process (IWA Respirometry Task Group) ».

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Mots clés : *traitement d'eaux résiduaires, boues activées, benchmark de simulation, commande de processus.*

SUMMARY

This paper presents a benchmark for a plant for biological treatment of wastewater, in order to evaluate, through simulations, different strategies of control. The benchmark represents the process of activated sludge in a configuration with pre-denitrification, for the treatment of domestic effluents, by removal of organic matter and nitrogen. It is based on models widely accepted by the international community and it is implemented in the Matlab/Simulink environment. The techniques of control here presented are typically used to control the process, such as: dissolved oxygen (DO) concentration-based control, respirometry-sbased control and nitrate concentration-based control, employing the classical proportional-integral (PI) controller.

Key-words: *wastewater treatment, activated sludge, simulation benchmark, process control.*

1 – INTRODUCTION

The basic objective of wastewater treatment processes is to achieve, at minimum use of energy and operational cost, a sufficiently low biodegradable matter concentration and low nutrient concentrations in the outflow together with minimal sludge production.

Wastewater treatment plants (WWTP) are complex multivariable systems, with many cross couplings, which incorporate a large number of biological and physical-chemical processes. Those processes are difficult to monitor and control. WWTP are typically large non-linear systems subject to large disturbances in the inflow and with an influent composition that is time varying and not well known. Their dynamics depend on the variability of the influent, and on the complexity of the biological, physical-chemical and biochemical phenomena. The process has a large range of time constants (from a few minutes to several days). As the process is very complex, it is difficult to ensure a satisfactory performance of the treatment system. A review of WWTP shows that their automation is normally minimal. A small number of plants are equipped with a few sensors and primitive control loops, mainly related to flow measurement and control and to monitor the basic performance of the plant for long periods of time. Since the seventies, when significant progress was achieved through the introduction of dissolved oxygen control, only small advances have been accomplished.

A way to improve the efficiency of the process may be to build new and large treatment plants, which is normally expensive and often impossible. Another way is to introduce advanced control techniques. This approach may provide a significant reduction in the large volumes necessary for wastewater treatment, an improvement in the quality of the effluent, a reduction in the use of chemicals and a possibility of saving energy and operating costs.

In this work, a benchmark that represents an Activated Sludge Process (ASP), in a configuration with pre-denitrification, including the processes of organic matter removal, nitrification and denitrification of domestic effluents, is implemented using Simulink/Matlab v.5.3 (MathWorks, 1999). The simulator is based on models largely accepted by the international community, namely the Activated Sludge Model No. 1 (ASM1) from IAWQ (International Association on Water Quality) (HENZE *et al.*, 1987), and the settler model of TAKÁCS *et al.* (1991). The following control techniques are also presented: DO concentration-based control, respirometry-based control and nitrate concentration-based control.

This work is consonant with the *European Program COST Action* (COST 624) and with the project *Respirometry in Control of the Activated Sludge Process* (IWA Respirometry Task Group).

2 – THE COMPLETE ACTIVATED SLUDGE PROCESS MODEL

2.1 Process Configuration

A schematic diagram of an activated sludge process with pre-denitrification is shown in *figure 1*. It is composed of a bioreactor (consisting of one anoxic zone and two aerobic zones, 13 m^3, 18 m^3 and 20 m^3, respectively) and a settler with 20 m^3. The influent flow Q_{in} is 4.17 m^3/h, with a concentration of biodegradable COD of 224 mg/L and a hydraulic retention time of 17.0 h. The internal recycle flow rate is $Q_{\text{int}} = 2Q_{in}$ and the external recycle flow rate is $Q_{sl} = 0.5Q_{in}$. The air flow rates in the aerobic zones are: $Q_{air\_2} = 0.044$ m^3/h and $Q_{air\_3} = 0.033$ m^3/h, respectively. In the anoxic zone no airflow rate is assumed. The process configuration was chosen to be close to a pilot-plant.

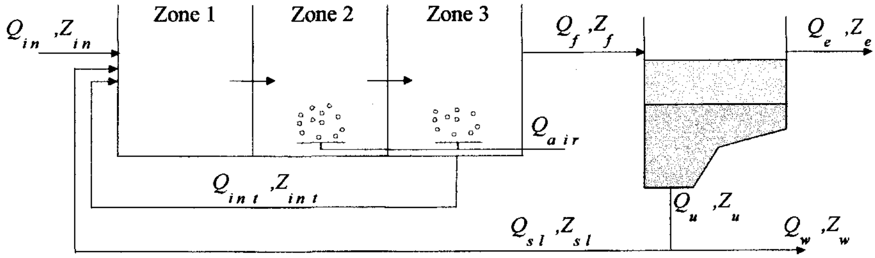

Figure 1 Layout of the benchmark.

2.2 Bioreactor Model

Each zone of the bioreactor is modeled using the ASM1 (HENZE *et al.*, 1987). The ASM1 is a mechanistic dynamic model with capacity of modeling the biological processes of carbon removal, nitrification and denitrification.

The parameters included in the IAWQ model are:

Heterotrophic biomass (X_{BH})	Autotrophic biomass (X_{BA})
Particulate substrate biodegradable (X_S)	Particulate organic nitrogen (X_{ND})
Inert particulate products (X_p)	Particulate inert organic matter (X_I)
Dissolved oxygen concentration (S_o)	Soluble ammonium nitrogen (S_{NH})
Soluble organic nitrogen (S_{ND})	Soluble nitrogen (S_{NO})
Readily biodegradable substrate (S_S)	Soluble inert organic matter (S_I)
Alkalinity (S_{ALK})	

The equations corresponding to the reaction rate for each of the state variables are given in JEPPSSON (1996).

In order to obtain the complete differential equations for the different states, a mass balance needs to be computed around each bioreactor. Using the system shown in *figure 1*, with a bioreactor divided in N zones or compartments (all the compartments are considered to have constant volume and to be ideally mixed), a general formula for the mass balance of each concentration is given by the following equations:

For $k = 1$ (first compartment in the input of the influent flow):

$$\frac{dZ_1}{dt} = \frac{Q_{in}Z_{in} + Q_{sl}Z_{sl} + Q_{int}Z_{int} - Q_1 Z_1}{V_1} + r_{Z_1}$$

$$Q_1 = Q_{in} + Q_{sl} + Q_{int}$$

For $k = 2$ to N

$$\frac{dZ_k}{dt} = \frac{Q_{k-1}Z_{k-1} - Q_k Z_k}{V_k} + r_{Z_k}$$

$$Q_k = Q_{k-1}$$

where Z_k (mg/L) is the concentration (particulate X or soluble S) in compartment k of the bioreactor, r_{Z_k} (mg/L·h) is the reaction rate of Z in reactor k, V_k (m^3) is the volume of compartment k and Q_k (m^3/h) is the flow rate in the outlet of compartment k.

For the special case of dissolved oxygen concentration ($S_{O,k}$):

$$\frac{dS_{O,k}}{dt} = \frac{Q_{k-1}S_{O,k-1} - Q_kS_{O,k}}{V_k} + r_{S_{O,k}} + \left(K_la\left(Q_{air}\right)\right)_k\left(S_{O,sat} - S_{O,k}\right)$$

where:

$K_la(.)$ = oxygen transfer function (1/h);

Q_{air} = air flow (that comes from the aeration blowers) (m^3/h);

$S_{O,sat}$ = oxygen saturation concentration (mg O_2/L).

Each zone of the bioreactor is modeled using the ASM1 model with the following assumptions and modifications:

- the S_I concentration is not considered as part of this study;
- the inert particulate organic matter (X_I) is a fraction of the organic matter that is not biodegradable. When organisms decay they form slowly biodegradable substrates which through hydrolysis can be used for formation of new organisms. A small fraction of the decayed organisms is biologically inert and it is called inert particulate products (X_p). In this work, these fractions are not of great interest and they are combined into one variable called particulate inert mass (X_{IP}), as follows:

$$X_{IP} = X_I + X_p$$

- K_la, considered to depend only on the airflow rate, is taken as:

$$K_la(Q_{air}) = 12.5 \cdot (1 - \exp(-10.08 \cdot Q_{air})) \qquad (h^{-1})$$

- the dissolved oxygen concentration is taken as: $S_{O,sat}$ = 8.6 mg O_2/L;
- an equation for the measurement of bacterial respiration rate (Oxygen Uptake Rate) was implemented, aiming to evaluate control techniques based on respirometry, as:

$$OUR = -r_{S_O} \qquad (\text{mg } O_2/(L \cdot h)$$

where r_{S_O} is the reaction rate for the IAWQ dissolved oxygen concentration.

The values of kinetic and stoichiometric parameters are the default values for a temperature of 15°C (see COST 624). For more details see SOTOMAYOR *et al.* (2001).

2.3 Settler Model

The settler is modeled employing a series of 10 layers (one-dimensional model), numbered from top to down, and it is based on the double exponential settling velocity proposed by TAKÁCS *et al.* (1991), where the solid mass balance in each layer is given by the following equations:

$$\frac{dX_{SS,1}}{dt} = \frac{1}{h}\left(J_{up,2} - J_{up,1} - J_{s,1}\right)$$

$$\frac{dX_{SS,i}}{dt} = \frac{1}{h}\left(J_{up,i+l} - J_{up,i} + J_{s,i-l} - J_{s,i}\right) \qquad 2 \leq i < m$$

$$\frac{dX_{SS,m}}{dt} = \frac{1}{h}\left(\frac{(Q_{in} + Q_{sl})X_{SS,f}}{A} - J_{up,m} - J_{dn,m} + J_{s,m-1} - J_{s,m}\right)$$

$$\frac{dX_{SS,j}}{dt} = \frac{1}{h}\left(J_{dn,j-1} - J_{dn,j} + J_{s,j-1} - J_{s,j}\right) \qquad m+1 \leq j < n$$

$$\frac{dX_{SS,n}}{dt} = \frac{1}{h}\left(J_{dn,n-1} - J_{dn,n} + J_{s,n-1}\right)$$

where:

X_{SS} is the sludge concentration or suspended solid (*SS*) concentration (mg/L);

h = 0.1 m, is the height of the layers;

A = 20 m^2, is the area of the settler transversal section;

n = 10, is the number of layers;

m = 7, is the feedlayer.

J_s is the flow of suspended solids, corresponding to gravity settling, defined by:

for $i = 1 : m-1$, then $J_{s,i} = \begin{cases} \nu_{s,i} \cdot X_{SS,i} & \text{if} \quad X_{SS,i+1} \leq X_t \\ \min(\nu_{s,i} \cdot X_{SS,i}, \nu_{s,i+1} \cdot X_{SS,i+1}) & \text{if} \quad X_{SS,i+1} > X_t \end{cases}$

for $i = m : n-1$, then $J_{s,i} = \min(\nu_{s,i} \cdot X_{SS,i}, \nu_{s,i+1} \cdot X_{SS,i+1})$

where X_t is the threshold of suspended solids concentration and ν_s is the double-exponential settling velocity function given by (TAKÁCS *et al.*, 1991):

$$\nu_{s,i} = \max\left[0, \min\left\{\nu'_0, \nu_0\left(e^{-r_h(X_{SS,i} - X_{\min})} - e^{-r_p(X_{SS,i} - X_{\min})}\right)\right\}\right], \qquad 1 \leq i \leq n$$

J_{up} is the solid flow, corresponding to the bulk up movement, defined by:

$$J_{up,i} = \frac{\left(Q_{in} - Q_w\right)X_{SS,i}}{A}, \qquad 1 \leq i \leq m$$

J_{dn} is the solid flow, corresponding to the bulk down movement, defined by:

$$J_{dn,i} = \frac{\left(Q_{sl} + Q_w\right)X_{SS,i}}{A}, \qquad m \leq i \leq n$$

The settler is implemented using the Takács model with the following assumptions and modifications:

– the soluble concentrations are implemented in the following manner:

$$\frac{dS}{dt} = \frac{Q_f}{V_{settler}}\left(S_{in} - S\right)$$

These concentration are considered homogeneous for all the settler layers, so that $S_{sl} = S_w = S_u = S_e$. For the special case of dissolved oxygen, it is considered zero in the sludge return and in the excess sludge flow, i.e. $S_{O,sl} = S_{O,w} = S_{O,u} = 0$;

– the total sludge concentration in the settler input is given by:

$$X_{SS,f} = 0.75 \cdot (X_{IP,f} + X_{S,f}) + 0.9 \cdot (X_{BH,f} + X_{BA,f} + X_{ND,f}) \qquad \text{(mg SS/L)}$$

The values 0.75 and 0.9 were taken from JEPPSSON (1996). They indicate the conversion factor of suspended solids to COD;

– the particulate concentrations in the treated effluent are calculated as follows, for example for $X_{IP,e}$:

$$\frac{0.75 \cdot X_{IP,f}}{X_{SS,f}} = \frac{X_{IP,e}}{X_{SS,e}}$$

where $X_{SS,e}$ is the SS concentration in the first layer. Similarly the equations for $X_{S,e}$, $X_{BH,e}$, $X_{BA,e}$ and $X_{ND,e}$ are obtained;

– the particulate concentrations in the sludge return and the sludge excess are calculated as follows, for example for $X_{BH,u}$:

$$\frac{0.9 \cdot X_{BH,f}}{X_{SS,f}} = \frac{X_{BH,u}}{X_{SS,u}}$$

where $X_{SS,u}$ is the SS concentration in the last layer. Similarly the equations for $X_{IP,u}$, $X_{S,u}$, $X_{BA,u}$ and $X_{ND,u}$ are obtained.

The settler parameters were obtained from data collected at a full-scale WWTP, in VANDERHASSELT (1999). These values were used along with the parameters for medium loading reported in TAKÁCS *et al.* (1991). The operational parameter values for the settler are given in SOTOMAYOR *et al.* (2001).

2.4 Wastewater characteristics (average values) and initial conditions

The wastewater concentrations were taken from the work of WIKSTRÖM (1993). The steady state values were used as initial values for the state variables (bioreactor and settler), which are shown in SOTOMAYOR *et al.* (2001).

2.5 Open-Loop Dynamic Response

The open-loop response of the process to the disturbances in the inflow wastewater, as shown in *figure 2*, are presented in *figure 3*, considering that the continuous line corresponds to the anoxic zone, the dashed line corresponds to the first aerobic zone and the dotted-dashed line to the second aerobic zone.

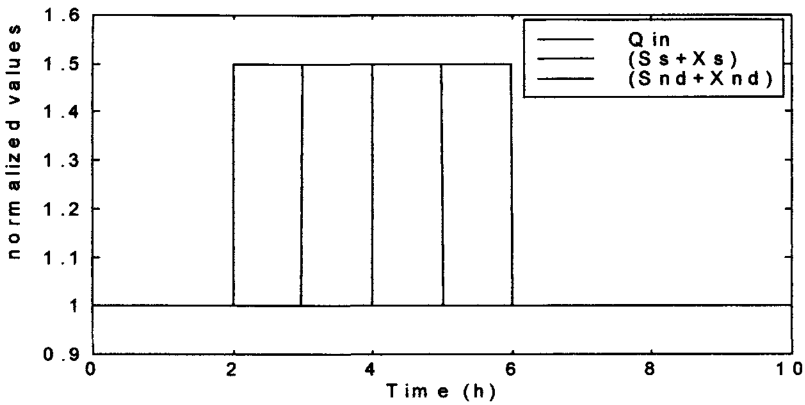

Figure 2 Disturbance in the influent wastewater Q_{in} = inflow rate, $(S_s + X_s)$ = total biodegradable organic matter, $(S_{nd} + X_{nd})$ = total biodegradable organic nitrogen) for open-loop response.

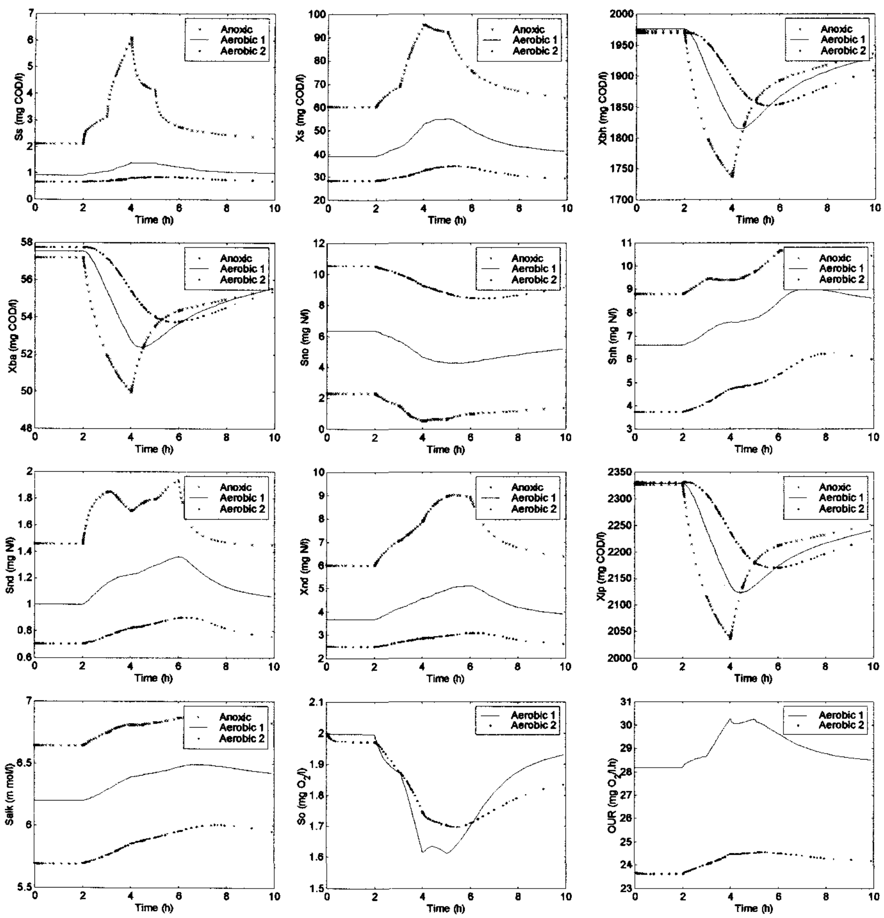

Figure 3 Open-loop responses to disturbances shown in figure 2.

3 – APPLICATION OF CONTROL STRATEGIES IN THE ACTIVATED SLUDGE PROCESS BENCHMARK

Here are presented some control techniques applied to the activated sludge process employing classical PI controllers. The main objective is to provide a way to compare the performance of advanced control strategies with PI controllers. Tuning of the PI controllers was not straightforward and heuristic methods (trial and error) proved to be necessary.

3.1 DO Concentration-Based Control

The DO concentration in the aerobic zone of an activated sludge process must be sufficiently high to supply enough oxygen to the microorganisms, in such a way that the organic matter be degraded and the ammonium be converted to nitrate. On the other hand, a very high DO concentration, which requires a high air flow, generates a large energy consumption and may also affect the sludge sedimentation. Furthermore, a high DO concentration in the internal recycle flow (Q_{int}) makes the denitrification process less efficient.

The objective of this strategy is to keep the DO concentration in zone 3, at a predetermined set-point (2 mg O_2/L) using a PI controller, through manipulation of the air flow injection ($0 \leq Q_{air\_3} \leq 0.3$ m^3/h). In zone 2 it is considered that the air injection is constant. The system is subject to several disturbances and the responses are shown in *figure 4*.

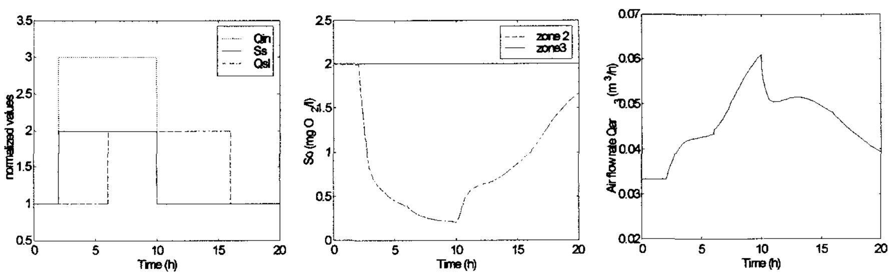

Figure 4 Disturbance sequence (Q_{in} = inflow rate; Q_{sl} = external recycle flow; S_s = inflow readily biodegradable substrate) and response of the process to DO concentration control.

3.2 Respirometry-Based Control

Respirometry is the measurement and interpretation of the bacterial respiration rate (OUR). The respiration rate corresponds to the oxygen consumed by the microorganisms per unit volume and per unit time (mg O_2/(L·h)). OUR is directly related to two important biochemical processes that must be controlled in a wastewater treatment plant: biomass growth and substrate consumption. A rapid decrease in OUR mainly implies that some form of toxic material has entered the plant or that the organic waste concentration has suddenly dropped. Next are presented two control techniques based on respirometry.

3.2.1 Active biomass control

The control strategy aims to keep the respiration rate in zone 3, at a predetermined set-point (23.6 mg O_2/(L·h)) using a PI controller, and implicitly to control the concentration of active biomass X_{BH} (deduced or inferred variable), through the manipulation of the external recycle flow ($0 \leq Q_{sl} \leq 12.5$ m^3/h). Since DO control is very important in the ASP (DOCHAIN *et al.*, 1995), the PI controller of the DO concentration is considered part of the plant layout (SPANJERS *et al.*, 1998). The system is subject to disturbances and the responses are shown in *figure 5*. The OUR set-point was chosen based on calculations in steady-state.

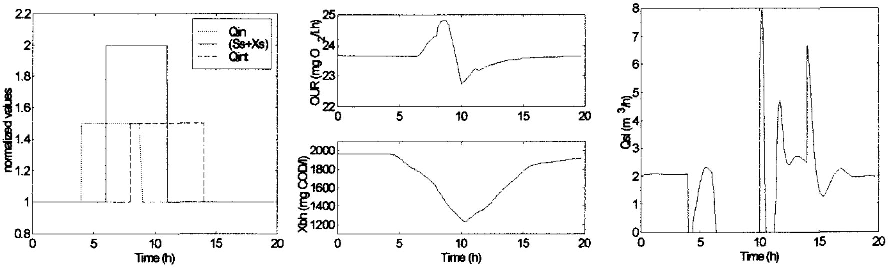

Figure 5 Disturbance sequence (Q_{in} = inflow rate; Q_{int} = internal recycle flow; ($S_s + X_s$) = inflow biodegradable organic matter) and response of the process to active biomass control.

3.2.2 OUR Control

The objective is to control the respiration rate in zone 3 at 23.6 mg O_2/(L·h), through manipulation of the air flow rate ($0 \leq Q_{air\_3} \leq 0.3$ m^3/h). The disturbances are, for instance, substrate concentration changes, pH or toxic changes, that will cause OUR to change. Such a change is noticed directly in the OUR value. However, in this case one needs to make further analysis to exactly determine what is causing the change in the OUR. In this case there is no DO control and, therefore, the DO concentration will change, but to some value that corresponds to the respiration rate. The results of the tests are shown in *figure 6*.

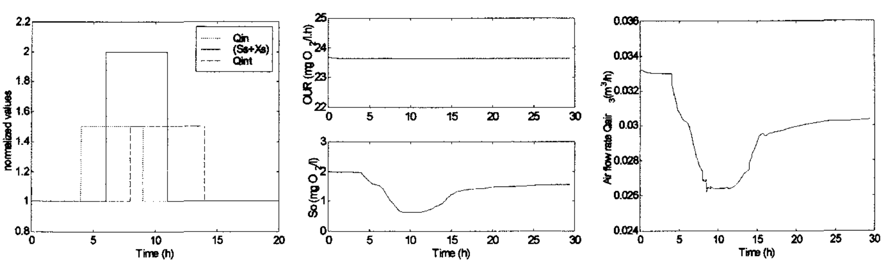

Figure 6 Disturbance sequence (Q_{in} = inflow rate; Q_{int} = internal recycle flow; ($S_s + X_s$) = inflow biodegradable organic matter) and response of the process to OUR control.

3.3 Nitrate Concentration-Based Control

The large variations in influent flow rate and wastewater composition, which are typical of WWTP, dictate a need for on-line control of the denitrification process in order to guarantee a sufficiently low effluent nitrate concentration. Two variables can be manipulated to achieve this objective: the external carbon dosage (ISAACS *et al.*, 1993; YUAN *et al.*, 1997; LINDBERG, 1997; BARROS and CARLSSON, 1998), to guarantee that (almost) all the recirculated nitrate is removed in the anoxic zone, or the nitrate recirculation flow rate (LONDONG, 1992; ANDERSSON *et al.*, 1995; SOTOMAYOR *et al.*, 2000), to control the amount of nitrate that is recirculated.

3.3.1 External carbon dosage control

Biological nitrogen removal in an ASP is dependent on a sufficient supply of easily degradable carbon compounds for the denitrifying bacterial population. An external carbon source (for example methanol, ethanol, acetate, primary sludge, etc) can increase denitrification rates and compensate for deficiencies in the influent carbon/nitrogen ratio (C/N). Dosing an insufficient amount will result in a high effluent nitrate concentration. Dosing too much will increase the costs considerably due to a higher carbon requirement, a higher sludge production, affecting the nitrification process, and increasing oxygen demand.

The objective is to maintain the nitrate concentration in zone 1, at a predetermined set-point (1.0 mg N/L) using a PI controller, through the manipulation of the external carbon source flow ($0 \leq Q_{ext} \leq 8.0$ L/h). The PI controller of the DO concentration is considered part of the plant layout. To simulate this technique some changes were made in the anoxic reactor model, to take into account the inflow of external carbon. To ease the implementation, an external carbon concentration similar to the mean value of the influent readily biodegradable substrate was considered. The disturbances and responses of the process are shown in *figure 7*.

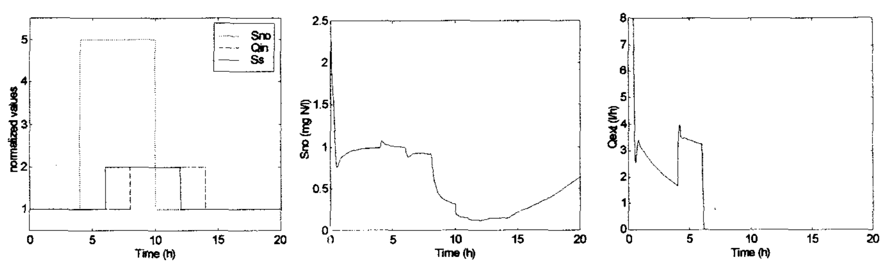

Figure 7 Influent disturbance sequence (Q_{in} = inflow rate; S_{no} = nitrate concentration; S_s = readily biodegradable substrate) and response of the process to external carbon dosage control.

3.3.2 Internal recycle flow control

In this strategy the objective is to keep the nitrate concentration in zone 1 at a predetermined set-point (1.0 mg N/L) using a PI controller, through manipulation of the internal flow rate ($0 \leq Q_{int} \leq 25$ m^3/h) rich in nitrate, from the last aerobic zone to the anoxic zone. The PI controller of the DO concentration is

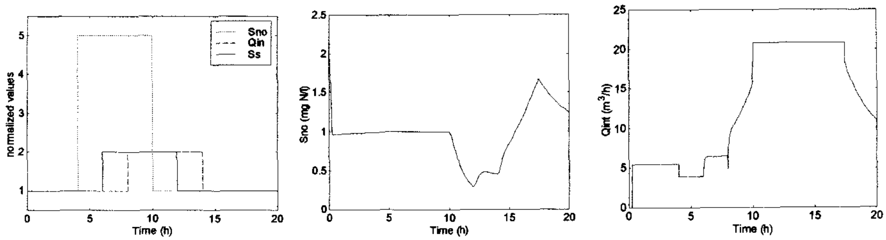

Figure 8 Influent disturbance sequence (Q_{in} = inflow rate; S_{no} = nitrate concentration; S_s = readily biodegradable substrate) and response of the process to nitrate recycle flow rate control.

considered part of the plant layout. The disturbances and the responses of the process are shown in *figure 8.*

4 - CONCLUSIONS

In this paper, a benchmark (a reference model) of a complete biological wastewater treatment plant has been developed in Simulink/Matlab, in order to evaluate, through simulation, the performance of different strategies of advanced control, including techniques based on respirometry. It was necessary for us to build this benchmark for two main reasons: first, to make available a truly open simulator in Simulink, a software that is easily accessed and used; second, a model which could be used in on-line optimization and advanced control. This is one important point: the model can be unsuitable from the experimental point of view, but very suitable to work as an internal model for optimization and advanced control.

The plant layout, the complete development of the simulator and a test in open loop are presented. The following strategies were selected to illustrate the application of automatic control in the benchmark (only with single-loop PI control): DO concentration-based control (dissolved oxygen control), respirometry-based control (active biomass control and bacterial respiration rate control) and nitrate concentration-based control (external carbon dosage control and internal recycle flow control). In the presented control strategies, the controlled variables are different, meaning that the objective of each control loop is different. There is thus no purpose in comparing the performance of the three proposed strategies.

The benchmark is being continuously updated and the next version will include adequate functions for on-line optimization of the process. The current version is available to interested users, who agree to report and document problems with the benchmark simulator. These users should request a copy of the benchmark from the corresponding author.

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REFERENCES

ANDERSSON B., NYBERG U., ASPEGREN H., 1995. Methanol and ethanol as external carbon sources for denitrification. *Nordic Seminar: Espoo*, Finland.

BARROS P., CARLSSON B., 1998. Iterative design of a nitrate controller using an external carbon source in an activated sludge process. *Water Science & Technology*, 37 (12), 95-102.

COST 624. Optimal management of wastewater systems. *The European Co-operation in the field of Scientific and Technical Research.* Website (http://www.ensic.u-nancy.fr/COSTWWTP/).

DOCHAIN D., VANROLLEGHEM P., HENZE M., 1995. Optimizing the design and operation of biological wastewater treatment plants through the use of computer programs based on a dynamic modelling of the process, Environment Research Programme, European Commission COST Action 682, Brussels, B-1049, Belgium, *Technical report 1992-95*, 132 p.

HENZE M., GRADY C., GUJER W., MARAIS G., MATSUO T., 1987. Activated sludge model No. 1. Task Group on Mathematical for Design and Operation of Biological Wastewater Treatment, International Association on Water Pollution Research and Control, London, SW1H 9BT, England, *Scientific and Technical report,* 1, 33 p.

IWA RESPIROMETRY TASK GROUP. *Respirometry in Control of the Activated Sludge Process.* Website (http://www.spb.wau.nl /mt/iawqstrproject/index. htm).

ISAACS S., HENZE M., SOEBERG H., KÜMMEL M., 1993. Activated sludge nutrient removal process control by carbon source addition. *Proceedings 12th World Congress of IFAC*, Sydney, Australia, 7, 417-420.

JEPPSSON U., 1996.Modelling aspects of wastewater treatment processes. PhD Thesis, Lund Institute of Technology, LTH-IEA-1010, 444 p.

LINDBERG C.-F., 1997. Control and estimation strategies applied to the activated sludge processes. PhD Thesis, Uppsala University, 214 p.

LONDONG J., 1992. Strategies for optimized nitrate reduction with primary denitrification. *Water Science & Technology*, 26 (5-6), 1087-1096.

MATHWORKS, 1999. Simulink v.3.0 – A program for simulating dynamic systems; and Matlab v.5.3, The MathWorks Inc., Natick, MA 01760, USA.

SPANJERS H., VANROLLEGHEM P., NGUYEN K., VANHOOREN H., PATRY G., 1998. Towards a simulation-benchmark for evaluating respirometry-based control strategies. *Water Science & Technology*, 37 (12), 219-226.

SOTOMAYOR O.A.Z., PARK S.W., GARCIA C., 2000. Nitrate concentration-based control of a pre-denitrifying activated sludge system. *IFAC Int. Symp. on Advanced Control of Chemical Processes,* Pisa, Italy, 14-16 June 2000, I, 213-218.

SOTOMAYOR O.A.Z., PARK S.W., GARCIA C., 2001. A simulation benchmark to evaluate the performance of advanced control techniques in biological wastewater treatment plants. *Brazilian Journal of Chemical Engineering*, 18 (01), 81-101.

TAKÁCS I., PATRY G., NOLASCO D., 1991. A dynamic model of clarification-thickening process. *Water Research*, 25 (10), 1263-1271.

VANDERHASSELT A., 1999. Monitoring and control of sludge sedimentation. PhD Thesis, Ghent University, Belgium.

WIKSTRÖM A., 1993. Simnon models for activated sludge systems, Dept. of Industrial Electrical Engineering and Automation, Lund Institute of Technology, Lund, S-221 00, Sweden, *Technical report LTH-IEA-7075*, 57 p.

YUAN Z., BOGAERT H., VANROLLEGHEM P., THOEYE C., VANSTENNKISTE G., VERSTRAETE W., 1997. Carbon dosage control for predenitrification processes. *Proceedings 4th European Control Conference*, Brussels, Belgium, 1-4 July 1997, paper TH-A-H 3.